GEOLOGIC MAP OF THE GALILEO REGIO QUADRANGLE (Jg-3) OF GANYMEDE

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DESCRIPTION OF MAP UNITS

LIGHT MATERIALS

ls **Smooth material**—Forms plains of moderate to high albedo; smooth except where secondary craters and crater chains are superposed. Characteristically associated with grooved material that it may overlie and grade into. Distinct boundaries with dark material. Appears to fill throughgoing groove pairs that penetrate dark material, and some exposures are bounded or crosscut by grooves. Representative area: lat 28° N., long 177°. Interpretation: Ice and less abundant silicate material that fill topographic lows; probably extruded along extensional fractures. May be younger or older than some of the grooved materials with which it is associated

lg **Grooved material**—Has high albedo. Forms relatively level surface interrupted by parallel to subparallel, curvilinear grooves, tens to hundreds of kilometers long; locally, grooves short and poorly ordered. Bounded in places by long, deep, linear, through-going grooves; distinct boundaries with dark materials. Young palimpsest materials and bright and slightly degraded crater materials superposed. Representative area: lat 53° N., long 176°. Interpretation: Ice, containing few rock fragments, that flooded areas where dark materials were displaced laterally or downward, or both. Groove formation resulted from pervasive development of extension fractures in the form of joints, faults, or grabens

DARK MATERIALS

[Constitute Galileo Regio, a subcircular area approximately 3,000 km across that is separated by lanes of light materials from other large areas of dark materials]

ds **Smooth material**—Has low albedo; smoother than other dark materials, with which it has indistinct boundaries. Very few small craters less than 10 km diameter superposed. Closely associated with furrows, especially in south half of quadrangle. Representative area: lat 25° N., long 156°. *Interpretation:* Facies of dark material, probably result of extrusion of ice and abundant rock fragments along extensional crustal fractures associated with furrows

df **Furrow material**—Forms arcuate northwest-trending troughs in undivided dark material flanked by rims that are estimated to be approximately 100 m high. Individual furrows 6 to 20 km wide, 50 km to several hundred kilometers long; material may compose much wider subparallel sets. Characteristically has scalloped outer margins and somewhat higher albedo than surrounding material. Spacing between arcuate furrows ranges from 15 km to 100 km and averages 50 km. Craters and palimpsests are superposed. Representative area: lat 48.5° N., long 165°. *Interpretation:* May be icy extrusive material that reached the surface through fractures associated with furrows; alternatively, may be upturned graben rims

d **Undivided material**—Has low albedo and irregular surface. Elements of roughness, largely degraded or partly buried by regolith, or both, are parallel short ridges and troughs and randomly distributed circular ridges. All craters, palimpsests, and furrows are superposed. Crater density relatively high but lower than in lunar highlands and on Callisto. Representative area: lat 30° N., long 167°. Correlative with dark furrowed material of Philus Sulcus quadrangle (Murchie and Head, 1989) and Uruk Sulcus quadrangle (Guest and others, 1988). *Interpretation:* Forms oldest surface recognizable on Ganymede; consists of ice-rock mixture that may overlie still older surface whose irregularities may be faintly visible

CRATER MATERIALS

[All craters interpreted to be of impact origin. Only craters larger than about 20 km in rim diameter are mapped]

c_3 **Material of bright craters**—Forms very bright ejecta deposits; bright rays common. Associated craters have relatively sharp rims. Ejecta deposits may extend outward as far as two crater radii but do not totally obliterate topography of underlying surface. Representative area: lat 21.5° N., long 169°. *Interpretation:* Ejecta, rays, and other crater materials associated with youngest craters. Postdates all other material mapped

c_2 **Material of slightly degraded craters**—Has albedo similar to or somewhat higher than that of surrounding terrain. Narrow rims subdued; some bright. Low-albedo material on some crater floors. Ejecta deposits, where present, may extend outward one to two crater radii; a few show shallow, outward-facing scarps similar to those of pedestal craters on Mars (Horner and Greeley, 1982). Representative area: lat 35.3° N., long 147°. *Interpretation:* Material of intermediate age. Craters degraded by some combination of impact, mass wasting, and ablation

c_1 **Material of highly degraded craters**—Has albedo similar to that of surrounding material. Highly subdued rims and degraded floors; original impact morphology in places barely discernible. No ejecta blankets visible. Representative area: lat 54.5° N., long 135.3°. *Interpretation:* Oldest material. Degraded by some combination of impact, mass wasting, and ablation

cm **Material of moat craters**—Forms large pit craters of intermediate albedo. From center outward, consists of a central smooth, flat or domed area surrounded by circular depression and inward-facing scarp, crater rim or platform, and outward-facing scarp. Diameters range from 30 to 70 km. Representative area: lat 29.5° N., long 165.5°. *Interpretation:* Impact crater, but origin of distinctive characteristics uncertain. Age comparable to that of ancient and old palimpsest materials

cs **Material of secondary craters and chains**—Forms chains and clusters of generally bowl-shaped craters less than 10 km diameter; most chains several tens of kilometers long. Albedo ranges from low to high. Representative area: lat 33° N., long 170°. *Interpretation:* Formed by impact of debris from large craters

PALIMPSEST MATERIALS

p_3 **Young material**—Forms multiring circular structures with irregular but low relief and albedo comparable to light material. Characterized by central smooth area surrounded by one or more concentric ridges and pitted material. Both bright and slightly degraded impact craters superposed. Ejecta forms uneven surfaces mapped as pitted terrain. Superposed both on light grooved and light smooth materials, and on dark materials. Diameter of outermost ring of structure in the southwest corner of quadrangle ranges from 250 to 300 km. Representative area: lat 24° N., long 179°. *Interpretation:* Large impact structures whose low relief is result of viscous relaxation or impact into low-strength materials, or both. Diameter of central smooth material may represent size of original excavation cavity (Casacchia and Strom, 1984; Passey and Shoemaker, 1982)

p2 **Old material**—Forms intermediate-albedo, subcircular features that have diffuse outer limits and superposed crater density similar to that of dark materials. Internal concentric ridges less discernible than in young material, but central smooth area still recognizable. No extensive ejecta deposits or secondary craters visible. Representative area: lat 27° N., long 148°. *Interpretation:* Same as for young palimpsest material

p1 **Ancient material**—Forms subcircular highly degraded structures slightly higher in albedo and similar in roughness to surrounding dark materials. Central smooth material common. Diffuse boundaries; no internal structures. Superposed on dark material. Representative area: lat 34° N., long 144.5°. *Interpretation:* Oldest palimpsests, probably formed soon after furrow systems

ps **Smooth material**—High-albedo circular plains, generally 70 to 90 km across, in center of young, old, and ancient palimpsests. Representative area: lat 27° N., long 148°. *Interpretation:* Origin uncertain; may represent area of original cavity of excavation later flooded or eliminated by viscous relaxation or doming

pp **Pitted material**—Albedo similar to that of target material. Surface rough or irregularly sculptured; high density of craters less than 7 km diameter; several discontinuous crater chains. Representative area: lat 25° N., long 177.5°. *Interpretation:* Discontinuous ejecta facies of young palimpsest material

Contact—Dashed where approximately located; dotted where buried
Ridge
Graben or grabenlike structure—Dashed where subdued
Scarp—Line at top; hachures point downslope
Linear depression—Dashed where subdued; mostly in dark materials
Deep, linear depression—Located in or at boundary of light materials
Furrow in dark materials—Dashed were subdued; schematic
Abundant, closely spaced furrows in dark materials
Sharp groove trend—Schematic
Subdued groove trend—Schematic
Shallow depression
Crater rim crest
Highly subdued or buried crater rim crest
Vague outline of highly degraded circular structure—Dotted where buried; possibly impact related
Moat crater—Central dome surrounded by circular depression; dome symbol schematic
Central peak of crater
Central pit of crater—Symbol outlines depression; some lie at summit of subdued domes
C**entral dome of crater**—Symbol schematic for small craters; locally transitional between central peaks and pits
Palimpsest ring
Light ejecta
Dark ejecta and dark crater floor
Field of secondary craters

INTRODUCTION

Ganymede, the largest of the 16 moons of Jupiter and the largest known satellite in the Solar System, is 5,262 km in diameter (Burns, 1986) and thus is larger than Mercury (diameter 4,878 km) and the Earth's Moon (diameter 3,476 km) (Hartmann, 1985, p. 108). Ganymede is the fourth largest body with a solid surface in the Solar System (after Earth, Venus, and Mars). In 1610, Galileo Galilei discovered four large Jovian moons, known as the Galilean satellites.Today, Ganymede is known to be the seventh moon, and the third Galilean satellite, outward from Jupiter. Ganymede is in synchronous rotation with Jupiter, and, with an orbital distance from Jupiter of 1.070 ¥ 106 km (Morrison, 1982), it is well within Jupiter's magnetosphere (Dessler, 1983).

Ganymede has a mass of 1.48 +/- 10^{23} g and a mean density of 1.94 g/cm3 (Burns, 1986). The relatively low mean density, combined with the detection of water absorption in its reflectance spectra (Pilcher and others, 1972), indicates that water ice is a major constituent of Ganymede; absorption spectra together with relatively high albedo indicate that water ice constitutes most of the surface material and may contain small percentages of oxidized iron-bearing minerals (Clark and others, 1986). Theoretical studies by Consolmagno and Lewis (1976) and Cassen and others (1982) support the hypothesis that Ganymede is a differentiated body with a rocky core and a water-ice mantle and crust.

The first spacecraft flybys of Jupiter and its satellites were by Pioneers 10 and 11 in 1973 and 1974, respectively, but only low-resolution, full-disc images were obtained (Morrison and Samz, 1980). Voyagers 1 and 2 made their closest approach to Ganymede in 1979 at distances of 115,000 km and 62,000 km, respectively (Morrison and Samz, 1980); they acquired high-resolution images of Galileo Regio on March 5 (Voyager 1) and July 9 (Voyager 2). The resolution of the best images of the Galileo Regio quadrangle ranges from 0.5 to 2.0 km/pixel. (See resolution diagram, this sheet.) Sun angles were 35° to 89° above the horizon (Smith and others, 1979a,b). The images of the northern part of the mapped area include the limb; these images are therefore highly foreshortened and do not permit detailed mapping. Many features shown in the poorly imaged eastern part of the quadrangle were identified on full-disc, far-encounter images (for example, Voyager 2 image 0528J2-2).

The first geologic map of Ganymede and thus of the Galileo Regio quadrangle was the preliminary, small-scale (1:42,500,000) map (Ferguson and others, 1982) of that part of Ganymede imaged by Voyager spacecraft; this map accompanied the description of the geology by Shoemaker and others (1982). A geologic map of Galileo Regio also was prepared by Casacchia and Strom (1984, scale 1:16,800,000), and a geologic map of the Galileo Regio quadrangle was made by Teeling (1986, scale 1:5,000,000).

Ganymede apparently is without high mountains and deep canyons. Study of the bright limb of Ganymede revealed that in most areas it has surprisingly little topographic relief, only about 1 km (Smith and others, 1979a). The apparent flatness possibly is the result of relaxation of the icy crust (Johnson and McGetchin, 1973; Parmentier and Head, 1981).

The quadrangle includes most of Galileo Regio, the largest region of contiguous dark materials on Ganymede. With the exception of the dark polar caps on Io, Galileo Regio is the only surface feature on the Galilean satellites easily identifiable from Earth (Smith and others, 1979b). That part of the regio in this quadrangle is a subcircular area of dark cratered material about 3,000 km across. It is in Ganymede's anti-Jovian hemisphere, whose central longitude is approximately 180° (Smith and others, 1979a,b). The mappable area of the quadrangle is limited in the east by the terminator and in the north by the limb.

The geologic mapping of the quadrangle followed the principles set forth by Wilhelms (1972). The map units were identified on the basis of albedo, morphology, crater density, and geometric pattern.

Two types of units dominate the surface of the quadrangle: dark, furrowed and cratered materials and light, grooved materials. The dark materials, which are much more abundant, have a low albedo, a rough texture, and a relatively high density of impact craters and are apparently the oldest surface units on the satellite. The less densely cratered and therefore younger light materials occupy about half of the imaged area of Ganymede and testify to intense resurfacing; in the map area, they are restricted to the western margin. Also in this quadrangle are crater materials and crater palimpsests (Smith and others, 1979b, p. 943, 945), which are high-albedo, subcircular structures of low topographic relief.

Shoemaker and others (1982) concluded that Ganymede has a “regolith of pulverized and mixed surficial materials” formed by (1) impact gardening by impact of meteoroids and secondary ejecta, (2) addition of meteoritic debris to surficial material, (3) sublimation of volatiles at low latitudes and possible reaccumulation at mid- and high latitudes, and (4) ion sputtering produced by the interaction with the Jovian magnetosphere. The low thermal inertia of the surface of Gany- mede demonstrates that the surficial material must be composed of fine, loosely packed, clastic particles (Shoemaker and others, 1982). Applying a lunar regolith model, they estimated the thickness of the regolith on Ganymede to be a few tens of meters in the anti-Jovian hemisphere in which Galileo Regio lies. However, Veverka and others (1986), using Monte Carlo simulations of regolith development, obtained a mean thickness of 320 m and a median thickness of 160 m for dark material and a mean thickness of 170 m and a median thickness of 45 m for light material.

Full-disc images of Ganymede obtained by Voyager 2 revealed the presence of north and south polar caps (Smith and others, 1979b). Poleward of 48° latitude, a continuous cover of relatively high albedo material is visible (Voyager image 0532J2-002); the material is interpreted to be a thin polar cap of water ice (Squyres, 1981a). Because albedo differences in the underlying material remain clearly evident in the area covered by the polar frost, the frost is thought to be very thin or, alternatively, to be pervasive in, and thus to have brightened, the underlying surficial materials (Helfenstein, 1986). Clark (1981) showed that as little as 0.1 mm of frost could produce the visible albedo of Ganymede's polar caps.

Several mechanisms have been suggested to explain the presence and distribution of polar frost on Ganymede (Purves and Pilcher, 1980; Sieveka and Johnson, 1982; Shaya and Pilcher, 1984), but each mechanism has problems (Johnson, 1985). Johnson proposed an alternative: because of Ganymede’s position well within the magnetic field of Jupiter, energetic ions may penetrate millimeters or less beneath the surface, producing a thin, light-scattering layer of ice poleward of 48° latitude, whereas south of that latitude, thermal reprocessing prevents the formation of such a layer (Johnson, 1985).

STRATIGRAPHY AND TECTONICS

DARK MATERIALS

Dark material is believed to be composed of water ice contaminated with dark silicate material (Pollack and others, 1978). Lucchitta and others (1992) suggest the darkening of the surface possibly is caused by (1) ion sputtering (Conca, 1981; Clark and others, 1986) or ablation of ice (Purves and Pilcher, 1980; Squyres, 1980b) that creates a surface concentration of silicate-rock particles, or by (2) contamination of the crust by dark projectile material (Pollack and others, 1978; Hartmann, 1980; Conca, 1981). The dark material may be polygenetic.

The area of dark material has a distinctive orthogonal grain or fabric created by conspicuous, gently arcuate, northwest-trending furrows and less conspicuous but more pervasive northeast-trending furrows. Still a third set, consisting of less abundant furrows spaced hundreds of kilometers apart, is oblique to the others. Inasmuch as furrows are not superposed on craters, the furrows must have formed when the crust was brittle enough to fracture but too weak to preserve sizeable craters (Casacchia and Strom, 1984). Because few furrows are modified by impact, the rate of furrow formation must have been greater than the impact rate (Casacchia and Strom, 1984).

The surface of the interfurrow areas is irregular and rough on a scale of hundreds of meters. In places, arcuate ridge segments, possibly the remnants of small craters, suggest that an older surface either was degraded by viscous relaxation or was partly covered by a material of endogenic origin. The lack of large crater-rim segments suggests that the process was one of viscous relaxation (Lucchitta and others, 1992). Also visible are the rims of abundant craters less than 10 km in diameter, presumably of impact origin; their crests characteristically have somewhat higher albedo than the surrounding dark material (Casacchia and Strom, 1984), suggesting either that they are of different material or that they have been modified in some way.

In addition to its low albedo, the dark material in Galileo Regio is distinguished by its relatively high density of craters ranging in size from the limit of resolution to about 50 km in diameter; only two craters have diameters as great as 100 km. Typical densities of craters greater than 10 km in diameter are 200 to 300 per 10^6 km^2; local densities may be as high as 400 (Shoemaker and others, 1982). Superposed craters cover the entire range of crater ages.

Undivided material (unit d), which occupies most of the quadrangle, has a normal albedo of 0.35 (Squyres and Veverka, 1981) and is in conspicuous contrast to the higher albedo light materials that occur along the western margin of the quadrangle. Smooth dark material (unit ds) is scattered in low-lying areas marginal to topographic highs, such as the rims of furrows and craters; it is more abundant in the southern part of Galileo Regio where it appears to embay materials of widely varied age, including dark material, furrow material, and old and young crater materials (Casacchia and Strom, 1984). In many places the smooth material is associated with arcuate furrows whose fractures may have provided it with pathways to the surface. Casacchia and Strom (1984) suggested that the increase in quantity of smooth dark material southward indicates the presence there of a thinner crust, where access to the surface would have been easier.

Furrow material (unit df) is interpreted to be a mixture of ice and rock that has extruded from the fractures that bound the northwest-trending arcuate furrows. These features are the dominant structural features in Galileo Regio and have been designated collectively as Lakhmu Fossae. The furrow material is so interpreted because the furrow-flanking ridges have a slightly higher albedo and because their outer margins are irregular. The arcuate furrows are irregularly spaced at intervals ranging from 15 to 100 km; average spacing is about 50 km. Their widths range from 6 to 20 km; their lengths from about 50 km to hundreds of kilometers (Casacchia and Strom, 1984); the length of the longest furrow, trending southeast from lat 50° N., long 175°, is 615 km. Their depth was estimated to be as great as 500 m, and they are bordered by ridges that rise to an estimated height of 100 m above the interfurrow terrain (Shoemaker and others, 1982). In at least one locality the distance across a furrow set from the outer limit of the flanking ridge on each side is 40 km (lat 32° N., long 165°). The furrows are linear, slightly sinuous, and mostly parallel to subparallel; they also display a variety of abrupt offsets and kinks. The furrows are interpreted to be grabens (McKinnon and Melosh, 1980; Casacchia and Strom, 1984). Alternatively, furrow rims may not be composed of extruded material but may be graben rims that were elevated as the graben floors rose in response to viscous relaxation of the faulted crust (Shoemaker and others, 1982).

Two other systems of linear fractures characterize the quadrangle and the region as a whole. The first system is Zu Fossae, which has fractures that trend northeast and thus are orthogonal to the arcuate furrows. These fractures are more densely spaced and more subdued. They are older than the arcuate furrows inasmuch as they are cut, but not displaced, by them.

The youngest of the three systems contains widely spaced (500 to 600 km apart) and less abundant furrows that cut both the arcuate and the orthogonal sets of fractures. These furrows are straight and relatively narrow; they trend north or north-northwest, oblique to the fractures of the other sets. Although their geometry suggests that they are not ring segments of a multiringed impact structure, they could be fractures radial to such a structure (Casacchia and Strom, 1984).

The origin of the furrows is uncertain. The crudely concentric pattern of the most conspicuous (the arcuate) set suggested to some that the furrows were created by a major impact event (McKinnon and Melosh, 1980; Shoemaker and others, 1982; Schenk and McKinnon, 1987). Murchie and Head (1989) interpreted the arcuate furrow set to be derived from an impact and superposed on fractures produced by tidal despinning, but also to have been modified by volcanism and extensional tectonism. Casacchia and Strom (1984), however, argued that the “...age relationships, morphology, and geometry of the furrow systems do not favor an origin by impact or tidal stressing.” They pointed to several problems with these interpretations: (1) absence of the fracture system predicted to accompany tidal despinning (Melosh, 1980); (2) lack of predicted increased spacing of fractures outward from the center of a multiring impact structure, according to the model of McKinnon and Melosh (1980); (3) dissimilar ages of the three fracture sets, which suggest that they were not produced simultaneously by the impact of a large meteor; (4) dissimilar morphologies of the rimmed furrows in Galileo Regio and the ridges of the Valhalla impact structure on a similar icy body, Callisto; and (5) the strong implication of furrow morphology that the furrows were produced by crustal tension rather than compression.

Further, the increasing quantity of dark smooth material southward in Galileo Regio and the apparent association of this supposed endogenic material with fractures presumed to have formed the furrows led Casacchia and Strom (1984) to suggest that an upwelling mantle plume of water uplifted a crust of uneven thickness, resulting in arcuate and concentric extensional fractures. They interpreted the other sets of furrows to be radial to subradial fractures also associated with the uplift. Schenk and McKinnon (1987) contended, however, that a hemisphere-wide upwelling plume is unlikely to have resulted in sufficient extension to have created the arcuate furrows; they and Murchie and Head (1989) favored an impact origin. The evidence is considered to be equivocal without additional, higher resolution data.

A large (300 km diameter) circular structure near the center of the quadrangle at lat 41° N., long 143° displays concentric ridges, furrows, grabens, and albedo markings reminiscent of the surface expression of a large impact structure. The origin of this feature is uncertain, but it probably is volcanic or impact related. If volcanic, this structure may record a hot spot where underlying materials have welled upward; however, the ripplelike surface morphology of the structure suggests that it was produced by the ancient impact of a large body (Underwood and others, 1986). The structure has neither the relatively high albedo nor the secondary impact craters commonly associated with large young palimpsests, nor does it resemble the two 250-km-diameter domes elsewhere on Ganymede described by Squyres (1980a). On the basis of this structure in Galileo Regio, a morphologically similar one in eastern Marius Regio (Jg–4), and part of a much larger one in northern Perrine Regio (Jg–2), Schenk and McKinnon (1987) suggested that, together with Lakhmu Fossae, these structures fit the large-crater part of Ganymede's crater-size-frequency curve and are therefore indicative of the impact origin of these structures.

LIGHT MATERIALS

Light materials, both smooth (unit ls) and grooved (unit lg), located along the western margin, occupy only about 5 percent of the quadrangle. Their relatively high albedo, 0.44 (Squyres and Veverka, 1981), may reflect the presence, at least at the surface, of a larger proportion of water ice than that found in the dark material. The boundaries with the dark units are distinct, in most places marked by linear depressions or boundary grooves interpreted as grabens. Although a few extensions of light materials into Galileo Regio can be identified (for example, at lat 35° N., long 179° and at lat 56° N., long 173°), no broad or consistent pattern of embayment of one material by the other is observed. Because crater densities in the light material are lower than those in the dark, the light material is known to be younger.

The smooth material, which is restricted in areal extent, has an albedo similar to that of the grooved material and is interspersed with it. The surface of the smooth material is almost featureless except for small superposed craters and rectilinear depressions (not mapped) interpreted as areas of subsidence.

The formation of the smooth material may be analogous to the flooding by basaltic lava of terrestrial rift zones (Squyres, 1981a, b). Because of extensional stress on Ganymede, subsidence of light grooved material permitted the extrusion of fluid onto the surface. The emplacement of smooth materials within Galileo Regio quadrangle must have been confined within the rifted zones because smooth materials have notably sharp boundaries.

In the Uruk Sulcus quadrangle to the south, a few craters more than 12 km in diameter are surrounded by dark halos; the low-albedo material of the halos may be derived from dark cratered materials buried 1.0 to 1.6 km beneath the surface (Schenk and McKinnon, 1985). This interpretation favors an origin by shallow burial of dark materials by light materials (Parmentier and others, 1982) rather than an origin from upwelling of liquid water following either the spreading apart of dark materials or their deep subsidence into the interior (Shoemaker and others, 1982). In the Galileo Regio quadrangle, a dark-halo crater in light materials occurs in Ur Sulcus at lat 52° N., long 178.5°; the crater is 60 km in diameter, the halo is 160 km in diameter.

Elsewhere on Ganymede, most of the light material is characterized by pervasive subparallel to parallel grooves that may be as deep as 700 m but average 300 to 400 m, are spaced at intervals of 3 to 10 km (5 to 6 km is typical), are locally hundreds of kilometers long, and have U-shaped troughs and somewhat flattened crests (Squyres, 1981a). In neither of the small areas of light grooved material in the map area are grooves as pervasive or as well ordered as elsewhere, which may reflect the dominant influence of the nearby boundary of Galileo Regio. The boundary has superposed on it craters as old as c_2 age that show only slight to no disruption, and it truncates ancient palimpsest material at lat 44° N., long 179°.

Grooves have been interpreted to result from extension (Smith and others, 1979a, b; Lucchitta, 1980; Squyres, 1980c, 1981a, b, 1982; Golombek and Allison, 1981; Parmentier and others, 1982; Bianchi and others, 1986; Murchie and others, 1986), which probably occurred during a period of crustal expansion resulting from planetary differentiation (Squyres, 1980c), phase changes in an ice mantle (Shoemaker and others, 1982), or global thermal effects (Zuber and Parmentier, 1984). Lucchitta (1980) and Shoemaker and others (1982) suggested that mantle convection may have driven the development of grooved terrain, although Squyres and Croft (1986) demonstrated that convection-derived stress would be minor compared with that produced by global expansion. It is possible, however, that global expansion was minimal and that light grooved materials resulted from a process unrelated to expansion, for example "violent hydrothermal activity" generated at the core-mantle interface (McKinnon, 1981).

In general, most grooves occur in the light grooved material, as do elongate zones of light smooth materials. Also a few areas of dark grooved materials occur in dark material. Thus, the term “grooved material” does not necessarily specify the same material as “light material,” although most light materials are at least somewhat grooved.

Extending more than 1,000 km along the northwest margin of Galileo Regio, that part of Ur Sulcus in the Galileo Regio quadrangle ranges in width from 25 to 180 km. Projecting for 360 km southward into Ur Sulcus from the northwest corner of the quadrangle, an irregular, elongate area of dark material is enclosed in light material. Much of the southernmost part of this area has an albedo that approaches that of the light material, which suggests that part of the material may be transitional between dark and light materials.

The boundary between Galileo Regio and Nippur Sulcus is marked locally by a conspicuous boundary groove, and Ur Sulcus also has a conspicuous, through-going, curvilinear groove about 600 km long. This long through-going groove is crosscut but not displaced by a similar curvilinear groove that extends southeastward and appears to extend into the dark terrain at lat 55° N., long 173°. There, light material may be just beginning to form at the expense of the dark material. At lat 54° N., long 175°, an elongate irregular area of grooved intermediate-albedo material may represent a transitional stage from dark to light material. Similar processes may have taken place along the southwest margin of Galileo Regio, where linear boundary depressions or grooves extend into the dark material in two localities: (1) at lat 28° N., long 176°, the penetration is about 200 km; (2) at lat 35° N., long 180°, the penetration is about 60 km. At lat 25° N., long 177°, a crudely rectangular area of intermediate-albedo material may be in transition from dark to light material, perhaps by fracturing and subsequent ice volcanism.

In the northwestern part of the quadrangle (for example, lat 55° N., long 173°), the boundary between the light and dark materials is orthogonal to the arcuate furrow system. At the southwest margin of Galileo Regio and outside the map area (lat 17° N., long 164°), the light material-dark material boundary is orthogonal to the radial furrow system. Thus, the west and south boundaries of Galileo Regio are each parallel to subparallel to one of the three furrow-system trends, suggesting that fractures associated with the furrows may have controlled the breakup of the dark terrain (Casacchia and Strom, 1984).

The best images of the boundary between light and dark materials in the map area do not provide definitive evidence of a difference in elevation, although the impression elsewhere is that the light material is slightly lower. Shoemaker and others (1982) observed that the dark material is higher than the adjacent light material at many places, and Lucchitta and others (1992) stated that in Memphis

Facula quadrangle to the southeast, the dark material of Galileo Regio locally is higher than the light materials of Uruk Sulcus along their east-west boundary.

PALIMPSEST MATERIALS

Ganymede's palimpsests, first clearly seen on Voyager 2 images of Galileo Regio, are bright, circular to subcircular features whose diameters in the map area range from 100 to 400 km and whose albedo is similar to that of the light materials. In the following discussion, the diameter of palimpsests is considered that of the total circular or subcircular relatively high albedo zone.

Palimpsests apparently were the earliest impact features formed after the development of furrows, when the crust became rigid enough to retain impact scars (Casacchia and Strom, 1984). The subdued topography of palimpsests is interpreted to be a result of viscous relaxation of the crust or of the low strength of the early crust during impact (Smith and others, 1979b; Parmentier and Head, 1981; Passey and Shoemaker, 1982; Croft, 1983), or both. However, Croft (1983) argued that palimpsests are not due to viscous relaxation; rather, they result directly from higher than normal impact velocities.

Palimpsests, which show several degrees of degradation, consist of three basic types of materials: ancient (unit p_1), old (unit p_2), and young (unit p_3). Ancient palimpsest material has a surface similar in roughness and crater density to the dark material and predates the light material. Most ancient palimpsests lack discernible internal structures, and many of these palimpsests contain areas of smooth palimpsest material (unit ps). Old palimpsest material has fewer superposed impact craters, and many of these structures contain central areas of smooth palimpsest material, some of which are surrounded by circular depressions and ridges. Young palimpsest material forms multiringed structures similar to impact basins observed on the surface of the terrestrial planets, although more flattened.

Of the 15 palimpsests in or partly in the quadrangle, 13 occur in the west half. The two largest and youngest (p_3) palimpsests are 400 km in diameter, near the southwest corner of the quadrangle, and 280 km in diameter, near the southeast corner. These young palimpsests are surrounded by ejecta deposits and fields of secondary craters that have degraded significantly the material on which they formed, creating an irregularly sculptured surface designated pitted palimpsest material (unit pp). Of the remaining 13 palimpsests, 6 are old (p_2) and average about 150 km in diameter, and 7 are ancient (p1) and average 110 km in diameter. This correlation of larger size of palimpsest with younger age does not exist everywhere on Ganymede; in the Uruk Sulcus quadrangle, for example, some of the largest palimpsests are the oldest (Guest and others, 1988).

On the outer part of some palimpsests, as at lat 35° N., long 152°, faint expressions (not mapped) of the underlying furrows are visible; therefore, the high-albedo material there cannot be thicker than the depth of the furrows, a few hundred meters or less (Shoemaker and others, 1982). That relation may also suggest that in such places furrow formation continued after the palimpsests were formed, but in any event the observation shows that the cavity of excavation of the palimpsest did not extend to the outer margin of the high-albedo zone (Casacchia and Strom, 1984).

The outer edges of the bright palimpsests are too sharp and even to be ejecta margins; they may be zones of seismic disruption, local heating, or both (Strom and others, 1981). The cavities of excavation probably are represented by (1) the bright areas (unit ps) at the center of most palimpsests (Shoemaker and others, 1982) or (2) the subdued inner rings or partial rings (Casacchia and Strom, 1984) observed in all of the palimpsests in the map area with the exception of four ancient ones.

Ancient palimpsests and highly degraded craters are known to be the oldest crater forms on Galileo Regio because they are overlapped by degraded craters. However, palimpsests and all craters greater than 10 km in diameter postdate the furrow systems (Casacchia and Strom, 1984).

CRATER MATERIALS

Impact craters in the quadrangle have a wide range of morphologies, ranging from fresh craters with bright rays, sharp and well-defined rim crests, and bright ejecta deposits to barely discernible features with highly degraded and flattened rims. The morphologic characteristics of impact craters also are related to size: the smallest, less than 20 km in diameter, have central peaks; intermediate sizes, 20 to 40 km in diameter, have central pits; and craters greater than 40 km in diameter commonly show terraces and domical floors. The interpretation and comparison of crater degradation states is complicated by (1) lack of data on the response of crustal ice-rock mixtures to hypervelocity impact and to subsequent relaxation by viscous flow, and (2) changing physical properties of the crust as Ganymede cooled.

Bright crater material (unit c_3) is the youngest unit of the region; ejecta of these craters overlap all other mapped units. The largest c_3 crater in the quadrangle, 75 km in diameter, is at lat 21.5° N., long 169°. There, bright rays extend outward as far as 150 km from its center.

Material of slightly degraded craters (unit c_2) has most of the attributes of bright crater material but has lower albedo and no rayed craters. Inasmuch as the unit is superposed on most other units of the map area and is the most abundant crater material, the impacts that produced it must have occurred throughout most of that part of the history of Ganymede recorded by the present surface.

Material of highly degraded craters (unit c_1) forms crater rims that characteristically are highly subdued, and the craters generally have no peaks or pits. The stratigraphic position of highly degraded craters shows that they formed relatively early; locally, they seem to overlap furrows, grooves, and crater palimpsests but also are, in places, disrupted and cut by furrows in the dark terrain.

Moat craters (unit cm) have an anomalously large central pit, a domed, smoother central area, and a depression or moat between the crater rim crest and the arched or domed crater floor. The floor of moat craters first flattened, then bowed upward as the crater rims and rim flanks subsided by viscous relaxation (Passey and Shoemaker, 1982).

Several chains of secondary craters (unit cs) also have been mapped. The crater Halieus (lat 35.5° N., long 168.5°) has several associated well-developed secondary crater chains, one more than 100 km long.

A crater at lat 28° N., long 133° has an outward-facing scarp at the apparent distal margin of the ejecta blanket and thus resembles ejecta-flow craters on Mars. Image resolution is not adequate, however, to identify radial-flow structures nor the thin, digitate flow lobes typical of the outer margin of the ejecta blankets of similar craters on Mars (Horner and Greeley, 1982).

Distinct, conspicuous, dark crater rays radiate outward for 50 km from a 20-km circular source at lat 59° N., long 150°. The resolution is poor at that latitude, but the rays appear to be centered at a depression about 100 km in diameter. Conca (1981) has suggested that the dark crater rays there and elsewhere on Ganymede are the result of ablation of projectile-contaminated ejecta, resulting in a surface-lag deposit of dark material. Ablation could result from sputtering of water by charged particles (Conca, 1981), still another of the possible effects of Jupiter's powerful magnetic field.

Many craters of varied sizes have straight rim segments or are polygonal in plan view. One or more of the straight segments is parallel to one or more of the furrow systems of the dark material, which may reflect control by the regional fracture pattern, either at the time of formation of the crater by impact or subsequently during isostatic adjustment and viscous relaxation of crater topography. Gravity-induced mass movements also may have occurred. Examples of such craters are at lat 23° N., long 125° (35 km diameter), lat 23° N., long 133° (50 km diameter), lat 30° N., long 154.5° (40 km diameter), lat 32° N., long 122° (50 km diameter), and the large craters Kulia, at lat 34.5° N., long 115° (95 km diameter), and Halieus, at lat 35.5° N., long 168.5° (90 km diameter).

Many dome craters are present in the Galileo Regio quadrangle and have crater diameters of 30 to 90 km and dome diameters of 10 to 50 km. Bianchi and Pozio (1985) and Moore and Malin (1988) studied the dome craters in the Galileo Regio quadrangle and elsewhere on Ganymede with inconclusive results. Dome craters may be the result of diapirism triggered by crater formation or by viscous relaxation following crater formation (Moore and Malin, 1988); their varied morphologies probably reflect the changing physical characteristics of the evolving crust of Ganymede (Bianchi and Pozio, 1985).

GEOLOGIC HISTORY

Ganymede's surface apparently does not provide direct evidence of the earliest phase of its geologic history, that is, heavy bombardment and accretion of particles of water ice and silicate-rich rock, nor of the period of early planetary differentiation into a mantle, core, and weak lithosphere. The first recorded event was the formation of dark materials approximately 4.0 to 3.8 billion years ago (Shoemaker and others, 1982). Viscous relaxation of the thin, weak lithosphere resulted in the disappearance of most evidence of the accretion process (Shoemaker and Wolfe, 1982) and “extensive resurfacing or viscous relaxation may have obliterated a Callisto-like crater population” (Murchie and Head, 1989).

The ice- and silicate-rich dark material may be the original global crust of Ganymede formed just after accretion, or it may be material extruded onto an older surface and altered by contamination with meteoritic material or by ion sputtering, or both, creating an increasingly dark lag deposit of silicate- and meteorite-rich material. As Ganymede cooled and the lithosphere strengthened, craters less than 10 km in diameter began to be preserved. The lithosphere eventually stiffened enough to permit widespread furrow formation, as the result of (1) an external event such as the impact of a large meteor (Smith and others, 1979; McKinnon and Melosh, 1980; Shoemaker and others, 1982; Murchie and Head, 1989) or (2) internal processes such as the upwelling of a large mantle plume of water ice (Casacchia and Strom, 1984).

The oldest set of furrows in the quadrangle is orthogonal to the arcuate set of intermediate age; the youngest set consists of those oblique to the other sets.The three sets must have formed relatively quickly inasmuch as they are older than craters greater than 10 km diameter. The earlier and larger impact events are represented by palimpsests; the later and smaller impact events, by craters of varied size and degree of degradation. In one locality just south of the map area, an arcuate furrow seems to have undergone reactivation, as it shows faint evidence of transecting the large palimpsest Memphis Facula. Dark smooth material, associated with the furrows, was emplaced from the time the furrows were formed through the period of formation of most craters.

Following the evolution of the furrow system and the emplacement of much of the dark smooth material, the thickening crust was broken apart and possibly sheared laterally as crustal expansion continued. Convection cells may have operated within the mantle to carry the water ice of the light material to the surface to fill the incipient voids developing between blocks of dark material or to overspread their surfaces as they foundered. The light grooved material formed by extension, but the details of the process remain obscure. In some areas, the light material has smooth surfaces that are younger than the grooved material. Young palimpsests also formed after the emplacement of light materials.

The bright-ray craters, the youngest features in the quadrangle, have not been significantly degraded. Processes that may be currently active on Ganymede are occasional meteorite impacts, mass wasting, and ablation resulting from either thermal migration of water, ion sputtering, or both.

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